Beam losses at injection energy and during acceleration in the Tevatron.

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Abstract

Protons and anti-protons circulate on helical orbits in the Tevatron. At injection energy (150 GeV) the lifetimes of both species are significantly lower on the helical orbits compared to lifetimes on the central orbit but for different reasons. There are also significant beam losses in both beams when they are accelerated to top energy (980 GeV)- again for different reasons. We report on experimental studies to determine the reasons and on methods of improving the lifetimes and losses for both beams.

INJECTION ENERGY

Higher proton intensities at injection in recent stores have not increased the proton intensities at low-beta and have therefore not had an impact on the luminosity. Proton losses at 150 GeV appear to grow proportionately to the intensity. The coalescing process in the Main Injector leads to larger transverse and longitudinal emittances with increasing intensity and is the likely cause for the increase in losses.

Typically proton lifetimes on the proton helix are about 2 hours, as seen in Figure 1 which shows the beam bunched intensity (FBIPNG) after protons are moved to the helix. The sharp drop at the beginning occurs when protons are moved from the central orbit to the helix. This jump is also seen in calculations of the dynamic aperture (DA). Figure 2 shows the DA (without beam-beam effects) of protons as a function of the momentum deviation. The DA drops by at least 3σ for all values of $\delta p/p$ from the central orbit to the proton helix. This figure also shows the strong dependence of the DA on the momentum spread. The DA of uncoalesced bunches (typically $\delta p/p < 2 \times 10^{-4}$) is about 2σ greater than for coalesced bunches which have momentum spreads $\delta p/p > 5 \times 10^{-4}$. Uncoalesced bunches are in fact observed to have better lifetimes both on the central orbit and the helix.

The importance of losses due to the longitudinal emittance was also seen during a study on December 3rd, 2002. When 12 bunches of coalesced protons were injected onto the proton helix, the bunch length decay lifetime was ~ 5.4hrs while the intensity lifetime was ~ 2.5hrs. Longitudinal scraping accounts for a significant fraction but not all of the observed intensity loss. Losses were found to increase sharply when the chromaticity was increased by 1 to 2 units in either plane - again emphasizing the importance of the momentum spread.

During this same study we also injected a single coalesced proton bunch on the anti-proton helix. The intensity evolution is seen in Figure 3. The intensity has a rapid decay at the start followed by a more gradual decay. This

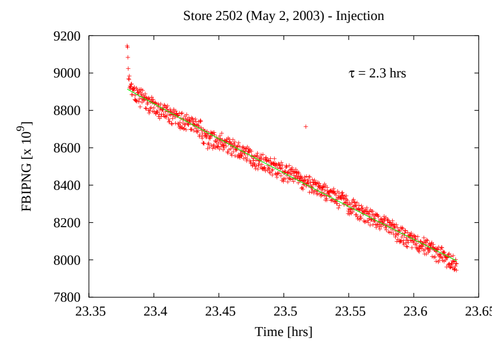

Figure 1: Proton bunched beam lifetime in Store 2502 (May 2, 2003).

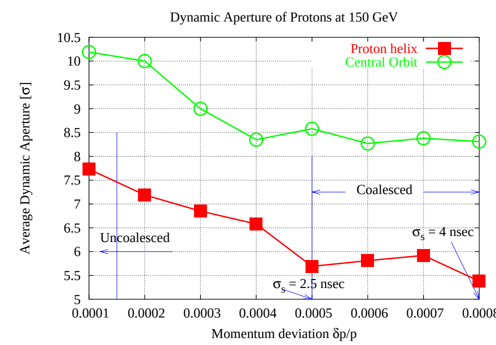

Figure 2: Dynamic aperture of protons on the central orbit and helix vs $\delta p/p$.

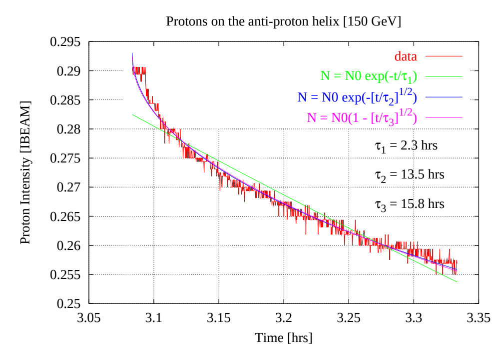

Figure 3: Beam intensity on the anti-proton helix (Dec 3, 2002).

decay is also typical of the anti-proton intensity decay in stores before the vertical damper was recommisioned. This decay is not well described by a single exponential decay law but heuristically found to be well described by a square root in the exponential $N(t) = N_0 \exp[-\sqrt{t/\tau}]$.

A simple model of constant phase space diffusion suffices to explain this behaviour. From the evolution of the particle intensity over time, it is evident that the extent of the antiproton distribution closely resembles the available aperture, whether it is physical or dynamic. For diffusion in one degree-of-freedom, the problem can be cast in terms of dimensionless variables $\tau \equiv (R/W_a)t$ and $Z \equiv W/W_a$, where R is the rate of change of the Courant-Snyder invariant, W, of a particle and W_a is the value of W corresponding to the limiting aperture (i.e., the admittance). The solution to the diffusion equation is[1]

$$N(\tau) = 2\sum_n \frac{c_n}{\lambda_n} J_1(\lambda_n) e^{-\lambda_n^2 \tau/4} \quad (1)$$

where the λ_n are the zeroes of the Bessel function $J_0(z)$, and the c_n are given by

$$c_n = \frac{1}{J_1(\lambda_n)^2} \int_0^1 f_0(Z) J_0(\lambda_n \sqrt{Z}) dZ \ , \quad (2)$$

$f_0(Z)$ being the initial particle phase space distribution (assumed to be radially invariant). In order to match the observed shape of the antiproton intensity variation in the Tevatron, the initial distribution needs to have an rms size comparable to the available aperture ($\sigma \approx a$). Once the correct shape has been established, the ratio of emittance growth rate to initial emittance sets the time scale: $\tau = 2(\dot{\epsilon}/\epsilon)(\sigma/a)^2 t$. In the Tevatron, the observed shape of the antiproton intensity curve over 15 minutes suggests that this time scale corresponds to $\tau \approx 0.04$ and that $a \approx \sigma$, or a rather uniform distribution in the available phase space. The antiproton beams coming from the Main Injector have transverse emittances (95%, normalized) of about 20π mm-mrad, are rather Gaussian, and the available transverse aperture is approximately 3σ or so. Also, the necessary emittance growth rate would have to be $\dot{\epsilon} \approx 16\pi$ mm-mrad/hr, exceedingly large. However, if we apply the same type of analysis to the longitudinal degree-of-freedom we find much more reasonable numbers. Namely, for an approximately uniform beam (after coalescing) entering a 4 eV-sec bucket, and a growth rate of 1/3 eV-sec/hr – all very consistent parameters for the Tevatron – then we get $\tau \approx$ 2 (0.33 eV-sec/hr/4 eV-sec)(0.25 hr)) = 0.042. This suggests that the behavior of the beam lifetime at injection is governed more by longitudinal effects. Using Eq. 1 and taking differing numbers of terms in the sum, we plot $N(\tau)$ over the range of interest of τ as well as $e^{-\sqrt{\tau}}$ in Fig. 4 . For this plot, we assume a uniform initial distribution within the aperture. The fact that we need to keep several terms ($n > 4$) in the expansion shows that several time scales are important.

More recently with the vertical dampers recommisioned, the vertical chromaticity has been dropped to 4 units at injection. At this lower chromaticity, the anti-proton intensity decays as a simple exponential.

Beam study with anti-protons only

In an anti-protons only study on September 10, 2002, we observed that these antiprotons were indeed much more

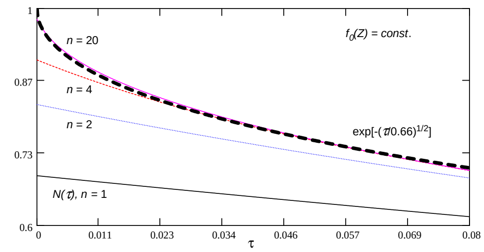

Figure 4: $N(\tau)$ using 1, 2, 4, and 20 terms in the sum. Also plotted is $e^{-\sqrt{\tau/0.66}}$.

stable than with protons present. A detailed study for all 36 bunches on the front porch showed that the lifetime is quite high, i.e. between 10.6hrs and 25hrs. We found a significant correlation of the lifetime with the vertical emittance seen in Figure 5. At that time there was a vertical aperture limitation due to a Lambertson magnet at C0. This was removed during the January shutdown.

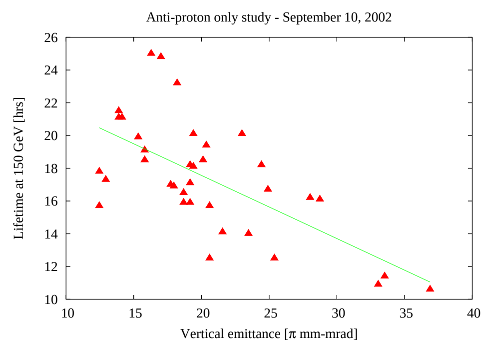

Figure 5: Anti-proton lifetime vs vertical emittance in an anti-proton only study.

ACCELERATION

Beam losses on the Tevatron ramp have been significant since the beginning of Run II (March 1, 2001). In the last year they have become the most significant contributor to the Tevatron inefficiency. Several phenomena take place - e.g., losses due to shaving on a physical aperture, limited DA due to machine nonlinearities and to beam-beam effects, loss of the DC beam, reduction of RF bucket area, etc. Figure 6 shows the variation of several parameters on the ramp in store 2328 (March 16, 2003, initial peak luminosity 40.6×10^{30} cm^{-2}s^{-1}).

Two dedicated experiments were done to identify the mechanisms that cause protons to be lost during the ramp. In both experiments, only proton bunches were injected and ramped. The conditions in the Booster and the Main Injector were adjusted so that the bunches had different intensities and emittances.

In the first experiment of September 24, 2002 we found that the losses were most strongly dependent on the lon-

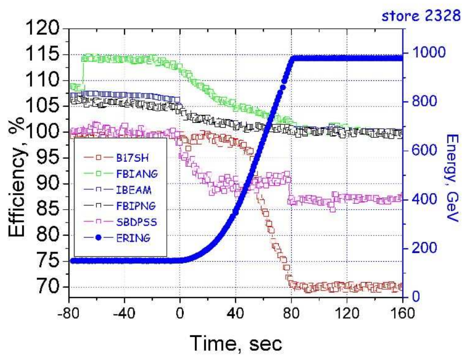

Figure 6: (color).Transfer efficiencies during the ramp in store 2328.

gitudinal emittance. For example, uncoalesced bunches which had the smallest longitudinal emittance lost less than 2% of their intensity during the ramp. At the other extreme, coalesced bunches with the largest longitudinal emittance lost about 12% of their intensity and furthermore their longitudinal emittance decreased by about 20% after the ramp. This implies that particles from the longitudinal tails were lost. We found a weaker dependence of the loss on bunch intensity and vertical emittance. In the second experiment on January 6, 2003 we attempted to isolate the dependence of the loss on the individual parameters in a controlled fashion. This time we also obtained the longitudinal profiles of the bunches at 150 GeV both on the central orbit and on the helix and again at 980 GeV. The longitudinal dampers were not turned on so the longitudinal oscillations of the bunches were not damped. We found that the most rapid loss occurs during the first 10 seconds of the ramp when the bucket area is decreasing - see Figure 7.

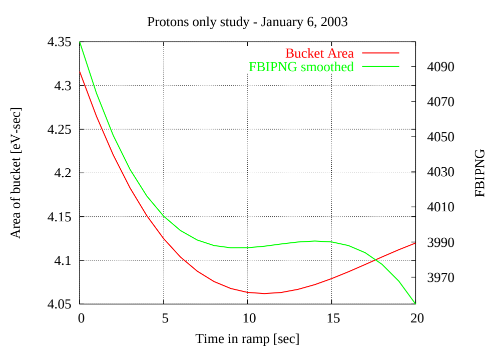

Figure 7: The bucket area and the beam intensity during the initial stages of the ramp. A large portion of the beam loss occurs while the bucket area is shrinking.

We found that the loss during the ramp was determined overwhelmingly by the longitudinal emittance and the longitudinal profile. Figure 8 shows the loss during the ramp as a function of the rms bunch length. The correlation is significant. Short coalesced bunches with nearly Gaussian profiles had the smallest losses ($< 2\%$) while long oscillating bunches had losses around 10%, seen in Figure 9. We found very little dependence on the bunch intensity. The same was true when we accelerated two proton bunches on the anti-proton helix.

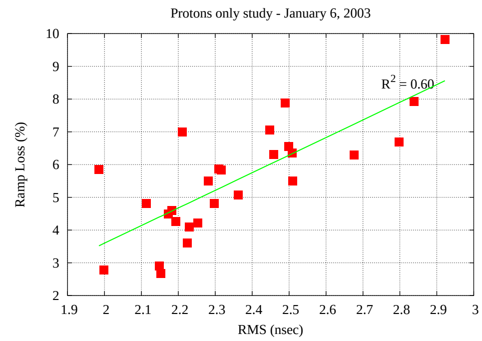

Figure 8:

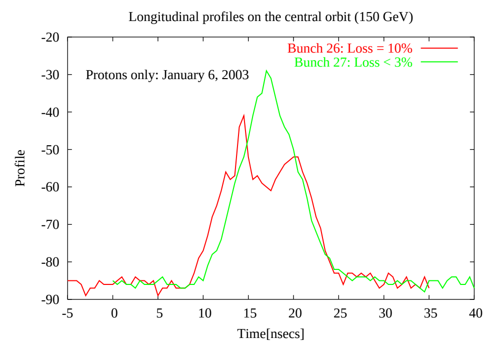

Figure 9: Longitudinal profiles of two bunches with nearly the same intensity and rms bunch length but very different losses during the ramp. The non-Gaussian oscillating bunch had greater losses during the ramp.

During the anti-proton only study on September 10, 2002, we accelerated the 36 bunches to flat top. We found that there was some loss (8.5%) of DC beam from the machine but the bunched beam current losses were very small ($< 2\%$) and within the noise of the measurement. Analysis of stores when both species are present shows a strong correlation of the anti-proton loss during the ramp with the anti-proton vertical emittance. These are due to the beam-beam interactions which have a larger impact on the larger amplitude anti-protons.

Beam losses during the ramp can be minimized if the longitudinal and transverse emittances are as small as possible. This would require better coalescing in the Main Injector, perhaps with the addition of longitudinal dampers. It might also help to turn on the longitudinal dampers during the ramp in the Tevatron.

REFERENCES

[1] D.A. Edwards and M.J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, Section 7.2, Wiley, New York (1993).